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Abstract: This paper aims at giving empirical content to the recent Basu & Weil (1998) theory of growth, in which localized innovation and differences in speeds of capital intensification can yield several patterns of international convergence and divergence. Using data envelopment analysis techniques, a decomposition is presented in which labor productivity growth is decomposed into growth due to localized innovation, creating spillover potential through investment and assimilation of knowledge spillovers. Regression analysis shows that convergence in the 1970s and divergence in the 1980s were mainly driven by processes of creating spillover potential, but that the other two factors also had significant impacts.

JEL: O14, O30, O40, O47.

Keywords: Economic growth, Productivity, Technological change, Data envelopment analysis, Spillovers.

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1. Introduction

Economists are still debating on the strengths and weaknesses of several concepts and measures of convergence. Nevertheless, there is agreement on the observation that productivity growth rates of the world's countries do not converge to a common rate. The traditional neoclassical model (Solow, 1956) predicted such 'absolute' or 'global' convergence, due to its assumption of a single worldwide production function featuring decreasing marginal returns to capital. In such a neoclassical world, differences in labor productivity growth rates can merely be a temporary phenomenon, caused by initial differences in capital intensities. This view, however, could not stand attempts to verify it empirically. Baumol (1986) and a host of subsequent studies strongly rejected the implied hypothesis of global convergence (see, e.g., Sala-i-Martin, 1996, and many references therein).

Broadly speaking, three avenues of research have been pursued to proceed towards a more satisfactory growth theory, which could account for the emergence of convergence clubs. First, the assumption of diminishing marginal returns to capital was relaxed in endogenous growth theories, such as Lucas (1988) and Romer (1990). Consequently, two countries with identical savings rates but different initial capital-labor ratios are likely to experience different productivity growth rates in these models.

Second, Mankiw *et al.* (1992) proposed to stick to the basics of the Solowian model, but to include human capital as a production factor, in addition to physical capital and (raw) labor. In this augmented Solow-model, steady state productivity growth rates can differ between countries, because they are dependent on the rates of investment in human capital. Thus, these models can generate divergence between groups of countries.

A third alternative is the 'technology gap' perspective. Proponents of this approach (e.g. Abramovitz, 1986, Verspagen, 1991, Fagerberg, 1994) argue that the Solowian assumption that all countries produce according to a common worldwide production function is wrong. They see technological differences as the prime cause for differences in GDP per capita across countries. Fundamental is the assumption that many countries are not able to benefit sufficiently from high-productivity production processes operated elsewhere. In this approach the basic two variables of interest are the innovation rate of the leader(s) and the rates at which the relatively backward countries can catch-up through assimilating new knowledge. For a given rate of innovation, a 'bifurcation rate' can be calculated. Countries with a catch-up rate below this rate will face an ever-increasing gap, whereas countries with a higher rate will ultimately reach growth rates similar to the leader.

Recently, Basu & Weil (1998) proposed a new theoretical model of international productivity growth dynamics, in which localized innovation is introduced as a force that can drive divergence. The model combines elements of the Solow model and the technology gap approach. Like the Solow model, the BW-model (henceforth, we will use this abbreviation) assumes that new knowledge about production technologies is immediately public. This new knowledge, however, is only relevant (or 'appropriate') for countries that produce according to technologies similar to the innovator's technology.

They will follow the innovator immediately, whereas other countries will not benefit at all, like in the technology gap approach.[1] Thus, innovation by leaders does not shift the production possibilities frontier as a whole, but only a part in the neighborhood of the specific combination of production factors currently in use by the leader. If a country, for whatever reason, is not able to invest sufficient resources to adopt a capital intensity similar to that of the leader, this 'localized innovation' (originally introduced by Atkinson & Stiglitz, 1969) yields divergence. BW claim that their theoretical model can generate outcomes that are more in line with reality than the results obtained from endogenous growth models.

The aim of this paper is twofold. First, and most prominently, it tries to give quantitative indications of the importance of localized innovation and BW's notion of appropriate technology for patterns of convergence and divergence. The analysis will be based on observations for a variety of countries between 1970 and 1990. Second, an extension of the model is proposed. Countries characterized by comparable capital intensities turn out to attain quite different labor productivity levels. In many cases, these differences persist for quite a long time, which might be considered as evidence for a slow process of assimilation of knowledge about appropriate technologies as stressed by Nelson & Pack (1999). Barriers to benefiting from 'spillover potential' should thus be taken into account. Data envelopment analysis (DEA) techniques, combined with a recently proposed decomposition of productivity growth and regression analysis, will provide a useful framework for empirical analysis of the sources of growth in the BW-model augmented with non-immediate spillovers. The methodology will be applied to Penn World Tables data on GDP, labor inputs and capital inputs. The decomposition results will be used in a convergence analysis based on regression techniques. Patterns of actual labor productivity growth are decomposed into three sources: localized innovation, assimilation of knowledge spillovers, and creating spillover potential through investment. The paper can be seen as a complement to the study of Kumar & Russell (2002) who used a comparable decomposition in a convergence analysis along the lines suggested by Quah (1996a). Our analysis, however, is linked much more strongly to a specific model of growth and offers more opportunities in terms of an economic interpretation of results.

The rest of the paper is organized as follows. In Section 2 the BW-model will be discussed in somewhat more detail and it is argued why assimilation should be included in the analysis. Further, the decomposition framework will be introduced and the relation between the theoretical and empirical approaches will be shown. Section 3 is devoted to a discussion of the data and the estimation of the set of best-practice production processes, which serves as the point of reference for the decomposition analysis. The empirical results will be presented and discussed in Section 4. Basically, this involves a decomposition of actual labor productivity growth rates into the effects of assimilation, creation of spillover potential through capital intensification and localized innovation. In Section 5, convergence and divergence of labor productivity rates will be studied on the basis of the contributions of the above-mentioned three sources of growth. Section 6 deals with an analysis of countries that emerge as outliers from the convergence regressions. It studies how the three sources of growth contributed to

[1] In the technology gap approach, countries may be too backward to benefit from spillovers. Generally, the degree of backwardness is measured by a proxy for social capabilities (Abramovitz, 1986), such as educational attainment, innovative activity, flexibility of credit markets and quality of infrastructure. In the BW-model, backwardness is expressed in capital intensities, although BW mention that their notion of capital can also include human capital. Irrespective of the exact meaning of capital, the concept of (in)appropriate technologies fits Abramovitz' notion of technological (in)congruence well.

the extraordinary performance of these ‘miracles’ and ‘disasters’, as suggested by Temple (1999). Section 7 concludes.

2. Decomposition of Growth in a Model of Appropriate Technology

Basics of the Basu & Weil (1998) model

BW model growth and technology transfer in a world in which knowledge is specific to particular combinations of inputs. These combinations are called ‘technologies’. Technologies are considered to be ‘similar’ if they are characterized by comparable capital intensities (capital to labor ratios). More advanced technologies have higher capital intensities. Each technology has its own maximum labor productivity level. For reasons that will soon become clear, we will denote these maximum labor productivity levels as ‘targets’. Targets for advanced technologies are higher than for less capital-intensive technologies. By producing with a specific capital intensity a country gains new knowledge about this particular technology and will improve the productivity level of this technology. In fact, countries not only improve the productivity of the specific technology they are using, but also raise the productivity levels of technologies with slightly different capital intensities. We will denote this process as ‘innovation’.

An important assumption in the BW-model is that new knowledge generated in one country is immediately available to all other countries. However, the transfer of knowledge is not immediately relevant, because countries need time to achieve a level of development that can take advantage of the innovation by technology leaders. Due to the assumption of technology-specific knowledge, a follower country can only benefit from this knowledge if it is operating (or starts to operate) at a similar capital intensity. Otherwise, the new knowledge generated is not ‘appropriate’ for the follower country.[2] History is important, since a follower country benefits from productivity improvements made by a leader country in the past. For a particular technology, a follower country inherits earlier productivity improvements and thus starts from a higher productivity level than the leader did. As a result of the joint effects of localized technological progress, appropriate technology conditions and differences in investment rates, the labor productivity levels of (groups of) countries will most likely grow at different rates.

An augmented empirical model of appropriate technology

The BW view of the world can be illustrated by Figure 1. It depicts the capital intensities and labor productivity levels of 53 countries, in 1990.[3] As BW suggest, technologies are ranked on the horizontal axis, indexed by their capital intensities. The vertical axis indicates the corresponding labor productivity levels that are attained. Two issues stand out immediately. First, more advanced technologies can generate higher labor productivity levels (compare the positions of Morocco (MAR), Canada (CAN) and the USA). This finding is in line with the BW assumptions.

However, a second finding is clearly not in line with the BW setup. It can be seen that technologies are operated at a variety of labor productivity levels (compare France (FRA) and the USA). This observation is important, especially since longitudinal comparison of the positions of countries indicates that such differences are often persistent. In fact, there is large literature on

[2] Basu & Weil give the example of advances in transportation technology in Japan in the form of a refinement of the newest maglev train. Such an advance will have very few spillovers to the technology of the transportation sector in Bangladesh, which relies in a large part on bicycles and bullock charts.

[3] Details on the construction of the variables will be given in Section 3.

impediments to knowledge transfer, even in the case when it is appropriate. Assimilation is a costly process including costs for the acquisition of new technology, adoption costs to overcome its tacit nature, adaptation costs to adapt the new technology to local circumstances, and more generally switching costs for the change from one technology system to another (Evenson & Westphal, 1995, Nelson & Pack, 1999). For the BW-model to have empirical relevance, such impediments to the transfer of knowledge specific to a technology must be taken into account. Therefore, our empirical analysis could be conceived as based on an 'augmented BW-model', in which a country's ability to assimilate appropriate knowledge is considered as a separate determinant of growth.

[Figure 1 about here]

The decomposition framework

Figure 1 suggests that the upper observations together constitute a type of frontier, which is roughly represented by a logarithmic curve running from the origin to the upper right. From a neoclassical perspective, this frontier is a single best-practice technology from which producers can choose the most favorable input combination given relative prices. However, from the augmented-BW viewpoint, this frontier should be seen as the set of technology-specific targets. It indicates for each technology the maximum labor productivity level at which it can be operated, given the knowledge available at that time.

We propose a decomposition of labor productivity growth into three sources: 'assimilation', 'creating potential' and 'localized innovation'. 'Assimilation' refers to the process where a country moves towards the frontier without moving it. It improves the level of productivity at which it is operating a particular technology, but it does not improve the level at the frontier. 'Creating potential' refers to the process of technology upgrading, measured here as capital intensification. By shifting to a more advanced technology a country opens up new possibilities for knowledge spillovers. This new technology will have a higher labor productivity target. 'Localized innovation' refers to movements of the frontier, that is improvements in the labor productivity targets of particular technologies. This is a movement of (part of) the frontier itself.

Suppose the frontiers for period 0 and 1 are given by F(0) and F(1). These are depicted in Figure 2 together with two observations for a particular country, indicated by *(0) and *(1).

[Figure 2 about here]

The total labor productivity ratio (y_1/y_0) is decomposed as follows: [4]

$$\frac{y_1}{y_0} = \left(\frac{y_1}{y_d} \cdot \frac{y_a}{y_0}\right) \cdot \left(\frac{y_c}{y_a} \cdot \frac{y_d}{y_b}\right)^{0.5} \cdot \left(\frac{y_b}{y_a} \cdot \frac{y_d}{y_c}\right)^{0.5}$$

or

4 See Maudos *et al*. (2000) for a similar decomposition framework.

$$\left(1+\hat{y}^{T}\right)=\left(1+\hat{y}^{A}\right)\cdot\left(1+\hat{y}^{C}\right)\cdot\left(1+\hat{y}^{I}\right) \qquad (1)$$

The first right hand side factor ('assimilation') measures the ratio of the vertical distance to the frontier in period 1 to that in period 0. A value of $\hat{y}^{A}$ larger than 0 thus indicates that the country under consideration has succeeded in realizing part of its spillover potential by improving the productivity at which it operates a particular technology. The second factor is a Fisher index for vertical movements of the target due to a shift towards higher capital intensities, that is horizontal shift of the country considered. If $\hat{y}^{C}$ exceeds 0, the new appropriate technology for the country allows for a higher labor productivity level if all spillover potential would be used. The third factor is a Fisher index for vertical movements of the target due to localized innovation. If the first two factors would equal 1, a positive value for $\hat{y}^{I}$ means that the country gained from innovation by the leader for the appropriate technology (which may well be the country under consideration itself).

3. Data and Frontier Methodology Analysis

Data

We used data on one type of output (GDP) and two types of inputs (labor and capital) from the Penn World Tables Mark 5.6. This data set gives GDP per worker and stocks of capital at international prices using expenditure PPPs from the International Comparison Program (see Summers & Heston, 1991, for details). To obtain the number of workers we divided real GDP (series RGDPCH) by real GDP per worker (series RGDPW). For capital stocks, we used the stocks of producer durables calculated as the non-residential capital stock per worker (series KAPW) multiplied by the share of producer durables in the stock (series KDUR). We focus on producer durables rather than on total capital stocks as we believe the former is more interesting from a technology perspective. Technology transfer and embodied spillovers are mediated through machinery rather than through structures (DeLong & Summers, 1991). The annual data span the period from 1965 to 1990 and cover 53 countries.[5]

Frontier estimation using Data Envelopment Analysis

In order to decompose labor productivity growth along the lines described above, a productivity frontier is needed. As discussed above, this frontier is the subset of observations that attain the highest labor productivity levels for the particular technologies they correspond to. Various approaches to the construction of production frontiers have been proposed and used in the literature. They either belong to the 'econometric' approach or to the 'programming' approach (see Lovell, 1993, for an overview). The econometric approach has a parametric nature and requires an a priori specification of the functional form of the frontier. In contrast, the programming approach is non-parametric, but has the drawback that it is deterministic and cannot accommodate for noise in the data. We will use the most common methodology within the programming approach (Data Envelopment Analysis, DEA) to

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5 PWT provides capital stock estimates for 63 countries, but we followed common practice by excluding less developed oil-exporting countries (Ecuador, Syria, Venezuela, Iran and Nigeria) and Sierra Leone because of its diamond mining activities. Further, we excluded Botswana, Nepal, Poland and Swaziland because data points were lacking for these countries. The total sample contained 1378 observations.

determine the frontiers.[6] DEA involves the use of linear programming methods to construct a piece-wise linear function over the data. Because of its non-parametric nature, it naturally allows for any form of localized technical change, which is an important feature in our framework.

Under the assumption of constant returns to scale in capital and labor, the determination of the enveloping frontiers for one input (C/L) and one output (Y/L) as depicted in Figure 2 can be stated as a rather simple linear programming problem (see e.g. Coelli *et al.*, 1998). Assume the data on the inputs and outputs are known for each of *n* countries. For the *i*-th country, they are represented by the scalars c_i and y_i respectively. Let **c** denote the (*n*x1)-input vector and **y** the (*n*x1)-output vector with observations for all countries. Then, the problem (to be solved for *i*=1..*n*) can be stated as :

$$
\begin{aligned}
&\max\text{imize}_{\,q,l}\ q_i \\
&\text{subject to :} \\
&-q_i y_i + \mathbf{y}'\mathbf{?} \geq 0 \\
&c_i - \mathbf{c}'\mathbf{?} \geq 0 \\
&n\mathbf{e}'\mathbf{?} = 1 \\
&? \geq 0
\end{aligned}
$$

Primes denote transposed vectors, **e** is an (*n*x1)-summation vector containing ones, **?** is an (*n*x1)-vector of constants and $?_i$ are scalars ($1=?_i<8$). The countries for which the envelopment problem yields $?_i=1$ together determine the position and shape of the frontier. Thus, $?_i-1$ is the proportional increase in output that could be achieved with the input quantities held constant and $1/?_i$ indicates the level of technical inefficiency in Farrell's (1957) sense. In our interpretation, these statistics indicate the spillover potential of country *i*. The model, an extension of the output-oriented model originally proposed by Charnes *et al.* (1978), allows for identification of a frontier which is convex. Increases of the target productivity are marginally decreasing with respect to increasing capital intensity as in the BW model.

In most DEA studies, the frontier at time *t* is calculated using data from period *t*. However, if panel data are available, the history of data up to *t* can also be included. There are two important reasons to calculate the frontier at time *t* in this way. First, 'technical regress' is ruled out. Because the production frontier is constructed sequentially, it can never shift inward. Such a possibility of 'technical regress' would have been awkward and hard to defend from a knowledge perspective on productivity, as it would involve 'forgetting'. Second, as discussed above, a crucial element in the BW-model of appropriate technology is the possibility for countries to use knowledge generated by technology leaders in the past. Labor productivity levels of past technology leaders should be attainable for latecomers. Hence, we used all data up to and including period *t* in our construction of the frontier at time *t*.[7]

A potential problem is that not all input-output combinations realized in the past have been observed as the data set starts only in 1965. It is possible that frontier techniques observed for the first years of the analysis are dominated by unobserved combinations in the past. In that case, part of what

[6] Although DEA was originally developed for firm-level analysis, it has frequently been used at the country level (see Färe *et al.*, 1994, Perelman, 1995, and Kumar & Russell, 2002). An example of country level analysis by means of an econometric frontier estimation methodology is Koop *et al.* (2000).

[7] For the actual calculation of the frontiers, we made use of the DEAP computer program developed by Tim Coelli (see Coelli, 1996).

would be interpreted as frontier movements would in fact be assimilation of knowledge associated with these unobserved appropriate technology targets. To accommodate this problem, we limit the decomposition analysis to the time span that starts five years after the first observations available to us. Hence, the first year of the analysis will be 1970, for which we will estimate the frontier on the basis of observations for the period 1965-1970.

4. Frontier and Decomposition Results

Frontiers

In Table 1 we provide an overview of the countries and techniques that determined the frontiers for 1970 and 1990. Apparently, the frontier for 1990 does not solely consist of techniques in use in 1990. For example, the labor productivity level generated by Canada in 1973 with the technology used in that country at that time, had still not been surpassed by any other country in 1990, notwithstanding that other countries had used the same technology in the meantime. In 1990 itself, for example, countries such as Greece, Portugal, South Korea and Yugoslavia produced at comparable capital intensity levels as Canada did in 1973, but labor productivity levels in these countries were much lower. As a consequence, the technique used by Canada in 1973 still remained on the frontier as the best technique for that particular technology up to 1990.[8]

[Table 1 about here]

Figure 3 provides a sketch of the progress that was made for various technologies over the past decades. The figure gives the maximum labor productivity levels in 1980 and 1990 as a percentage of the corresponding targets in 1970, for a range of capital intensities. It is clearly shown that the most remarkable advances have been made in the technologies characterized by high capital intensities. Whereas technologies with an intensity below $30,000 were barely improved during the period from 1970 to 1990, for technologies with capital intensities of more than $70,000 improvements of 10 percent and more were attained.[9] Interestingly, since 1980 innovation stagnated for a large range of intermediate technologies (roughly between $7,000 and $44,000). This is an important finding, given that in 1990 19 out of the 53 countries operated in this range of technologies, including countries such as Argentina, Thailand, Portugal and South Korea. This means that these countries could not benefit at all from progress being made at the frontier. The finding of a highly localized nature of innovation stresses the empirical relevance of the BW model, making it an important potential driver of divergence in the world economy.

[Figure 3 about here]

8 The number of observations that shape the frontiers does neither remain stable over time, nor does it increase monotonically. The minimum number of such techniques was 7 for 1973, the maximum 13 for both 1989 and 1990.

9 The only exception is innovation by Morocco in the 1980s, which moved the frontier at very low capital intensity levels.

Decomposition results

The estimated frontiers can be used to decompose a country's labor productivity growth into three sources, as indicated in equation (1): assimilation of spillovers (movements towards the frontier), creating spillover potential through capital intensification (movements along the frontier) and innovation (movements of the frontier). In Figure 4 we provide such a decomposition for a limited number of countries, to illustrate the usefulness of the augmented BW model for analyzing growth. The left-hand side graphs show the development of actual labor productivity and the movement of the target, that is, the maximum labor productivity level attainable for the country's technology as indicated by the frontier. The right-hand side graphs show changes in the actual labor productivity levels and its sources: assimilation, creating and innovation. Depicted is the cumulative index, taking 1970 as the base year. The 'total' line corresponds to the 'actual' line in the left-hand side figure.

A variety of growth patterns can be discerned. On the one hand, there is the case of the United States which relied on innovation as the main source of labor productivity growth, accounting for more than 70% (see Figure 4a) of actual growth in the period 1970-1990. In contrast, growth in Taiwan was mainly due to a rapid increase in capital intensity and increasingly by assimilation, that is, moving towards the frontier. This indicates that Taiwan first created the opportunities for rapid productivity growth by a swift move up the technology ladder, and later on started to effectively assimilate these new technologies, albeit from a very low level of efficiency as shown in the left-hand side figure. As it still not operated at those parts of the frontier where innovation took place, it could not benefit at all from innovations.

The growth decomposition of West Germany illustrates that assimilation can also be a very effective source of growth. Up to 1980, growth was mainly driven by improving the efficiency of the operation of technologies that were gradually upgraded. After 1980, Germany entered the technology range where innovation took place and as a result it could benefit from innovation, making it the most important source of growth. The development in Mexico is completely different. It is characterized by an initial increase in the target labor productivity followed by a decrease. This went together with a long period of stagnation in the actual labor productivity level. In 1982, default of Brazil on its foreign debt obligations resulted in a 'lost decade' for the whole Latin-American continent. In particular, with soaring inflation, falling exchange rates and starvation of foreign capital, capital-intensity levels actually decreased quite dramatically. In effect, the target moved towards lower maximum labor productivity levels (see left-hand figure) and assimilation of knowledge about less-advanced technologies took place, arguably of the less-desired kind.

[Figure 4 about here]

5. Sources of convergence and divergence

The previous section showed that innovation has been limited to a particular range of capital intensive technologies. Some countries benefited from global innovation, others did not. Further, some countries created spillover potential at a fast pace, whereas others appeared not to be able to increase their capital intensities to a substantial extent. Finally, some countries managed to assimilate knowledge related to appropriate technologies, while others did not get any closer to their target or even lost ground in this sense. Thus, all three sources of productivity growth identified in our augmented BW-model could well exert forces towards divergence of labor productivity growth rates. In the remaining sections of this paper, we will systematically investigate what impacts assimilation, creating spillover potential and innovation have had on the relative productivity growth performance of countries in the period 1970-1990.

In the literature, a number of empirical concepts to study convergence have been proposed. In this section, we will look at the performance of the 'representative' country. We will do this by looking at the well-known concepts of s-convergence and ß-convergence.[10] Quah (1996a,b) argued that unambiguous conclusions about convergence within a sample of countries can only be drawn by means of tools that study the dynamics of distributions (of productivity levels) themselves. Investigations of the dynamics of summary statistics on distributions only, could lead to misleading results due to the emergence of a bimodal distribution of productivity levels.[11] However, since we are not only interested in convergence or divergence of productivity levels *per se*, but also in the factors underlying the performance of countries that did very well or very poorly, we will adopt a different perspective. As we will show, a study of ß-convergence also lends itself much more to a techno-economic interpretation than Quah's analysis. Afterwards, in the next section, we will investigate how the three determinants of productivity growth specified in the augmented BW-model affected the productivity growth performance of countries that apparently deviated from the general pattern. Many of these 'miracles' and 'disasters' are countries that switched from one peak to the other (either way) in Quah's bimodal productivity distributions.

Productivity gaps: s-convergence

First, we will look at the dynamics of the mean and standard deviations of labor productivity gaps to the US. In the literature, a steady decline of standard deviations of productivity levels (normalized by taking logarithms) is called s-convergence. We will follow this definition, but consider the leader country as a specific point of reference. We will not only look at s-convergence of actual labor productivity levels, but also have a look at this type of convergence for the gaps between actual productivity levels and their corresponding targets on the one hand, and the gaps between targets and the target of the US on the other. This will give a first impression of the relative contributions to the actual pattern of (i) assimilation, and (ii) creating spillover potential and localized innovation.

In Figure 5, the dynamics of three means and the corresponding standard deviations are depicted for the sample of 52 countries (53 countries minus the US). First, we have computed m(y^T) and s(y^T), the mean and standard deviation of the distribution of actual labor productivity levels relative to the US level.[12] Referring to the frontier for period 0 in Figure 2, these indicators refer to the distribution of the y_0/y_c ratios. Second, the curves denoted by m(y^A) and s(y^A) are obtained by calculating the means and standard deviations of y_0/y_a These indicators give insights into the effects of assimilation with respect to the appropriate technology. Third, m(y^{CI}) and s(y^{CI}) refer to the distributional dynamics of targets. Thus, these statistics relate to the joint effects of creation of spillover potential and localized innovation. They are computed on the basis of the distribution of the ratios y_a/y_c[13].

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[10] See e.g. Baumol (1986) and Barro & Sala-i-Martin (1991) for early contributions on both notions of convergence. A symposium in the *Economic Journal* was devoted to discussions of the strengths and weaknesses of various concepts and measures (e.g. Sala-i-Martin, 1996, Bernard & Jones, 1996, and Quah, 1996b)

[11] See Kumar & Russell (2002) for a convergence decomposition study along the lines set out by Quah (1996a).

[12] Although Table 1 indicates that Luxembourg was labor productivity leader in 1990, we will relate all levels to the US, in view of the fact that this country has attained the highest productivity levels during almost the entire period considered here.

[13] Note that this approach cannot distinguish between effects of creating spillover potential and effects of localized innovation, since both sources of productivity growth affect the labor productivity levels associated

[Figure 5 about here]

The mean ratio to the US for actual labor productivity levels has gradually increased over time (that is, the mean gap decreased). Simultaneously, the standard deviations of the ratios to the US rose, be it at a slow pace. Together, these findings indicate that there was a general tendency towards convergence in our sample, but that some countries caught up at faster paces than others, which may even have fallen behind. This result is in line with much of the evidence presented by earlier convergence studies.

As mentioned, our decomposition model allows us to analyze not only patterns of actual labor productivity convergence, but also of its sources. We find a slightly different pattern with regard to productivity growth as a consequence of assimilation. Until the beginning of the eighties, the mean ratio of labor productivity levels associated with actual techniques to the frontier of technology-specific best techniques remained relatively constant, with the exception of a drop after the oil crisis. This leads us to the conclusion that assimilation generally did not contribute to convergence in these years. In most of the 1980s, this changed. The gaps to the frontier steadily became smaller. The standard deviation did hardly change, which indicates that assimilation of knowledge was a rather universal contributor to convergence in this period.

Interestingly, Figures 5a/b indicate that the observed convergence of actual labor productivity levels in the 1970s was predominantly fuelled by catching-up in terms of targets. In theory, two phenomena could account for this. First, innovation could have been localized within ranges of technologies with lower capital intensities than the US technology. Figure 4, however, contradicts this explanation by and large. The second explanation, which states that many countries managed to adopt much more capital-intensive technologies with higher maximum productivity levels, seems much more in line with results in earlier convergence analyses. The standard deviation of the gaps gradually decreased, which suggests that this tendency was caused by developments within a substantial number of countries.

From 1980 onwards, things seem to have changed rather dramatically. The gaps of technology-specific targets to the US targets started to increase. Figure 4 already indicated that innovation was strongly localized within high capital intensity technologies. Further, the standard deviation of the ratios turns out to have increased relatively strongly after 1980. Apparently, some countries were able to benefit from high-end localized innovations, whereas others were not. Moreover, while attaining further productivity growth through assimilation, countries might have had difficulties in continuing to adopt increasingly capital intensive technologies.

Our s-convergence results based on the decomposition framework can be summarized by two statements, on which the remainder of our analysis will focus.

1) Assimilation on the one hand and localized innovation and spillovers as stressed by BW on the other require specific attention, although they produced a relatively steady average productivity catch-up of lagging countries to the US.
2) In specific time periods (the 1970s and the 1980s, respectively), the performance of countries show increasing variability for a number of sources of productivity growth differentials. This implies that it is insufficient to investigate ‘representative behavior’. Special attention should be devoted to outliers.

with targets.

Productivity gaps: ß-convergence

Another popular notion of convergence focuses on the question whether initially lagging countries tend to grow faster than countries initially close to the leader. If so, so-called ß-convergence prevails. Studies of ß-convergence can both be found in the mainstream tradition (in which it is mostly ascribed to the effects of diminishing returns to investment, see e.g. Mankiw *et al.*, 1992) and in the technology gap literature (in which the main reason for ß-convergence to occur is the gradual assimilation of knowledge related to new innovations, see e.g. Verspagen, 1991).

The general regression equation we estimate is a fairly simple one:

$$\hat{y}_i^T - \hat{y}_{US}^T = \alpha_T + \beta_T \log\left(\frac{y_{0,i}}{y_{0,US}}\right) + \varepsilon_i^T \quad , \tag{2}$$

in which hats denote annual growth rates, averaged over the period under consideration. The left-hand side of the equation represents the productivity growth performance of a country relative to that of the United States (the notation is as in equation (1)). A negative b_T would indicate that backward countries do better than countries close to the US, as we chose the logarithm of the ratio between the country's initial labor productivity and the US initial labor productivity as the exogenous variable.[14] A negative b_T would not necessarily mean, however, that most countries close the productivity gap to the United States. A negative value for a_T would imply that the average country would lose in productivity terms to the US, if it would have had an initial productivity level identical to the US level (indicated by a zero logarithm on the right hand side).

We report estimates for three periods, 1970-1990 and the subperiods 1970-1980 and 1980-1990. It should be noted that the explanatory variable is always evaluated in 1970. Hence, the performance of a country in 1980-1990 is also linked to its productivity position in 1970. The results are depicted in Figures 6a-6c.

[Figure 6 about here]

In all three panels, the horizontal zero-line indicates the productivity growth rate exactly equal to the US. Apparently, the majority of countries grew faster than the US in terms of labor productivity in the early subperiod, but slower in the later period. The dotted logarithmic curves represent the estimated relationships.

[Table 2 about here]

Table 2 shows that the slopes do not deviate from 0 at the 10% significance level, except for the 1980-1990 subperiod.[15] The positive estimate implies that very backward countries on average performed

[14] Note that we do not allow for parameter heterogeneity. Verspagen (1991) and Durlauf & Johnson (1995) proposed specifications in which the ability to benefit from (non-localized) spillovers -as indicated by $ß_T$- is dependent on the size of the initial gap. We support this view of nonlinear catch-up, but are of the opinion that such an analysis would be beyond the scope of the present paper.

[15] White's procedure to compute heteroscedasticity-consistent *t*-values was used.

worse than less backward countries in this decade. In other words, divergence prevailed. The constant term turns out to be positive for the entire period and, in particular, for the early subperiod.
This is in line with the upward tendency emerging from Figure 5a (m(y^T)) and suggests that the follower countries were on average more conducive to productivity growth than the US. The huge variety of growth performances as evidenced by all three panels is reflected in the very low values for R^2.

To get more insight into the role played by the determinants of productivity growth as specified in our augmented BW-framework, we also ran regressions similar to equation (2), based on the decomposition results. That is, we specified regression equations as follows:

assimilation:
$$\hat{y}_i^A - \hat{y}_{US}^A = \alpha_A + \beta_A \log\left(\frac{y_{0,i}}{y_{a,i}} \Big/ \frac{y_{0,US}}{y_{a,US}} \right) + \varepsilon_i^A \tag{3a}$$

creating spillover potential:
$$\hat{y}_i^C - \hat{y}_{US}^C = \alpha_C + \beta_C \log\left(\frac{y_{a,i}}{y_{a,US}} \right) + \varepsilon_i^C \tag{3b}$$

localized innovation:
$$\hat{y}_i^I - \hat{y}_{US}^I = \alpha_I + \beta_I \log\left(\frac{y_{a,i}}{y_{a,US}} \right) + \varepsilon_i^I \tag{3c}$$

[Table 3 about here]

The regression results are presented in Table 3. The second column of the top panel shows that differences in assimilation performance may have widened the gap between the US productivity level and the productivity levels of other countries. Only for the entire time span, however, the negative coefficient for a_A is significant at 10%. In both decades, countries that initially operated well below the frontier managed to get faster to the frontier than countries relatively close to the frontiers (negative estimates for $ß_A$). Assimilation of knowledge with respect to appropriate technologies thus appears to be an important source of convergence.

The middle panel indicates that creation of spillover potential by capital intensification has had a far from steady impact on convergence throughout the period under consideration, unlike assimilation. For the period as a whole, a clear tendency towards convergence due to creation of spillover potential is revealed. This result appears to have been driven entirely by the developments in the first decade, however. For this subperiod, the absolute value of the estimated negative coefficient $ß_C$ is large, and the autonomous productivity growth through creating spillover potential was substantial. In the period 1980-1990, though, this source of labor productivity growth has caused a clear tendency towards divergence, which is in line with the results for actual labor productivity convergence documented in Table 2.

The bottom panel of Table 3, finally, gives a more systematic insight into the convergence effects of localized innovation. The estimated intercepts are significantly negative, irrespective of the specific time span considered. Moreover, the estimated slope coefficients are positive, although not significant at 10% in the later decade. Both results reveal that localized innovation has put a pressure towards divergence on labor productivity growth rates. It should be noted, though, that the estimated ßs are an order of magnitude smaller than the corresponding estimates presented in Tables 3a and 3b.

This section studied the empirical implications of the sources of productivity growth that we specified in our augmented BW-framework for worldwide patterns of convergence and divergence. Localized innovation appeared as a force towards divergence, whereas assimilation had effects in the opposite direction. Creating spillover potential turned out to be important for convergence in the 1970s, but provided an important contribution to divergence of actual productivity levels in the 1980s. The next section does not look at the relative importance of the three determinants for the general pattern, but investigates how influential these factors were for the performance of countries that clearly deviated from this general pattern.

6. Outlier Analysis: Miracles and Disasters

Complementary to the 'representative' behavior as found from the regression analysis, we would also like to study the performance of 'non-representative' countries. In this respect, we follow a suggestion made by Temple (1999) to focus more in depth on 'miracles' and 'disasters'. Did productivity growth 'miracles' mainly benefit from assimilation, or from one or both of the other two sources of labor productivity growth in the augmented BW-model? And which of these determinants accounted for the bad fate of productivity growth 'disasters'? In our view, such questions are at least as important as the questions answered in the previous section.

As a first step 'miracles' and 'disasters' should be identified. We do this in a rather straightforward way. The upper and lower curves in Figure 5 indicate the bounds of the (two-sided) 80% confidence intervals associated with regression equation (2). Miracles and disasters are identified by positions above the upper bound and below the lower bound, respectively. We followed a similar procedure for regression equations (3a-c), to identify the outliers with respect to the three separate sources of productivity growth.

The leftmost columns of Table 4 indicate the outliers with regard to actual labor productivity growth. The miracles are the usual suspects, i.e. the Asian Tigers. Not surprisingly, the disasters are mainly located in Africa and Latin America. Interestingly, miracles in the first subperiod tend to emerge as miracles in the second subperiod, too. A similar, but less pronounced, tendency can be observed for disasters. Thus, the actual performances of 'non-representative' countries appear to be characterized by some persistence.

Hong Kong, identified as one of the growth miracles, seems to owe much of its performance to effective assimilation. It appears as an assimilation miracle in both subperiods. Another miracle, Korea, seems to have followed a different route. During the period 1970-1980, the country created much spillover potential, at the cost of an assimilation disaster. It invested heavily in more capital-intensive technologies but without learning how to use them in a way comparable to the appropriate technology leaders. In the second subperiod, though, it proved capable of performing outstandingly with respect to both assimilation and creating spillover potential. Taiwan also appears as a miracle with regard to actual productivity growth in both subperiods. This was based on an extraordinary performance in creating spillover potential in the first period and 'representative' behavior with regard to the other sources of productivity growth in both subperiods. [16] Rapid growth in Thailand is not due

[16] See Timmer (2000) for a much more elaborate study of the productivity performance of East-Asian countries.

to a particular source, without extreme contributions of either assimilation or capital intensification. None of these countries benefited in particular from innovations as they operated technologies that are still far away from the technologies in use in innovating countries.

[Table 4 about here]

Once more, the innovation miracles exemplify the highly non-linear pattern of worldwide innovation. For both subperiods, the positive outliers are found at the extreme ends of the spectrum of technologies. In the high capital intensity range, countries like Switzerland, Germany and Canada apparently benefited most strongly from innovation. Interestingly, Chile, Zimbabwe, Malawi and Morocco turn out to be miracles in benefiting from localized innovation as well, at least during one of the subperiods. Some of these countries, with a very low initial target labor productivity level amounting to 10-15% of the US target level, emerge as localized innovation miracles due to Morocco's performance.[17] This country managed to push the frontier outward, whereas the frontier remained stable within a range of higher capital intensities (see Table 1).

Turning our attention to disasters with regard to actual labor productivity growth, we find that a lack of ability to create spillover potential has been the main cause of bad performance. Countries like Zambia, Peru and Jamaica also lost ground due to the localized nature of innovation. The majority of these innovation disasters are Latin-American countries that used mid-range capital intensity technologies, for which the 1970 maximum labor productivity levels amounted to about 45% of the US level. These countries were identified as innovation disasters since both at lower and higher capital intensity levels at least some innovation took place (see Figure 3).

7. Conclusions

This study provides an empirical framework to study the labor productivity growth performance of countries from a perspective suggested by a recent model of economic growth (Basu & Weil 1998). A prominent feature of this model is the localized nature of innovation. Innovations for capital-intensive technologies will not affect the performance of capital-extensive technologies, and the other way round. We augment the model by relaxing the assumption of immediate spillovers. Assimilation of technologies new to a country is a costly process as stressed by Nelson & Pack (1999). As a result, many countries perform well below the best practice at similar technologies.

A decomposition framework suggested by the augmented BW-model was implemented by estimating a global production frontier, which indicates for each technology the maximum labor productivity level at which it can be operated, given the knowledge available at that time. . Actual labor productivity growth was decomposed into the effects of assimilating knowledge pertaining to particular technologies, creating potential to benefit from more productive technologies, and localized innovation. Analysis of convergence processes suggests that localized innovation causes a tendency towards divergence. At low levels of capital intensity, hardly any innovation was found, whereas the frontier was steadily pushed at high capital intensities. In the 1970s, both assimilation and creating spillover potential through capital intensification appeared to contribute to convergence. In the 1980s,

[17] Malawi's (1970-1980) miracle status is an artifact. This country did not benefit from any shift of the frontier at all in this period. Given its extremely low initial capital intensity, the estimated loglinear relationship predicts an inward shift of the frontier for low capital intensities. Such technical regress was ruled out by our construction of the frontiers.

this picture changed dramatically, as creating spillover potential contributed forcefully to apparent overall divergence of productivity growth rates.

The convergence regressions enabled us to have a closer look at the performance of outliers. The extraordinary growth rates found for Asian 'miracle' countries turned out to be the result of a non-homogeneous mix of contributions. Hong Kong relied heavily on assimilation, whereas Korea and Taiwan started their advance by creating huge spillover potentials, which were partly realized later on. Many disasters were found in Latin-America, apparently due to negative tendencies with regard to creating spillover potential. In 1990, many developing countries were stuck within a range of technologies characterized by low capital intensities with little potential for further growth by means of spillovers.

In our view, the results of this study ask for a number of future research efforts. First, the analysis is based on aggregate economies. Some of them experienced rapid industrialization, whereas others had already entered the stage of tertiarization and still others generated their outputs predominantly in agricultural activity. Sector-specific analyses would add to the empirical operationalization of the appropriate technology concept. Second, it may be worthwhile to link both assimilation performances and creating spillover potential performances to determinants like schooling, infrastructure, openness to trade, etc. In earlier convergence studies, such factors turned out to be critical but it is unknown which factors relate most predominantly to knowledge assimilation and which to creating potential.

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Table 1: Input-output combinations on frontier in 1970 and 1990

Frontier in 1970				Frontier in 1990			
		C/L (a)	Y/L (b)			C/L (a)	Y/L (b)
Malawi	1965	159	846	Malawi	1965	159	846
Ivory Coast	1965	947	2,674	Morocco	1990	2,489	6,770
Morocco	1965	1,719	4,428	Spain	1965	6,503	12,451
Spain	1965	6,503	12,451	Argentina	1969	8,337	14,110
Argentina	1969	8,337	14,110	Argentina	1971	9,350	15,029
Spain	1969	10,699	16,024	Spain	1969	10,699	16,024
Canada	1966	27,151	23,145	Argentina	1980	14,462	17,828
Canada	1969	32,098	24,746	Canada	1973	34,969	27,426
USA	1966	53,205	29,152	Canada	1979	43,970	29,191
USA	1968	60,603	30,192	Canada	1988	73,186	34,521
USA	1969	63,652	30,637	Canada	1989	80,240	35,069
				USA	1989	114,128	36,859
				Luxembourg	1990	177,813	37,903

Notes: (a) Producer durable capital stock per worker (in 1985 International $)
(b) GDP per worker (in 1985 International $)

Table 2: Regression results, actual labor productivity growth vs. initial gaps to the US.

Period	a_T	$ß_T$	R^2
70-90	0.0055 (p=0.009)	0.0021 (p=0.313)	0.018
70-80	0.0127 (p=0.000)	-0.0026 (p=0.192)	0.025
80-90	-0.0015 (p=0.630)	0.0055 (p=0.053)	0.049

Table 3: Regression results, by source of productivity growth.

Assimilation (equation 2a)			
Period	a_A	$ß_A$	R^2
70-90	-0.0055 (p=0.096)	-0.0112 (p=0.012)	0.132
70-80	-0.0063 (p=0.195)	-0.0116 (p=0.045)	0.062
80-90	-0.0051 (p=0.112)	-0.0116 (p=0.034)	0.089
Creating spillover potential (equation 2b)			
Period	a_C	$ß_C$	R^2
70-90	0.0000 (p=0.989)	-0.0053 (p=0.014)	0.057
70-80	0.0036 (p=0.028)	-0.0196 (p=0.000)	0.558
80-90	-0.0006 (p=0.827)	0.0129 (p=0.012)	0.113
Innovation (equation 2c)			
Period	a_I	$ß_I$	R^2
70-90	-0.0018 (p=0.000)	0.0016 (p=0.001)	0.193
70-80	-0.0006 (p=0.025)	0.0032 (p=0.000)	0.730
80-90	-0.0037 (p=0.000)	0.0014 (p=0.132)	0.052

Table 4: Miracles and disasters as identified from regression equations

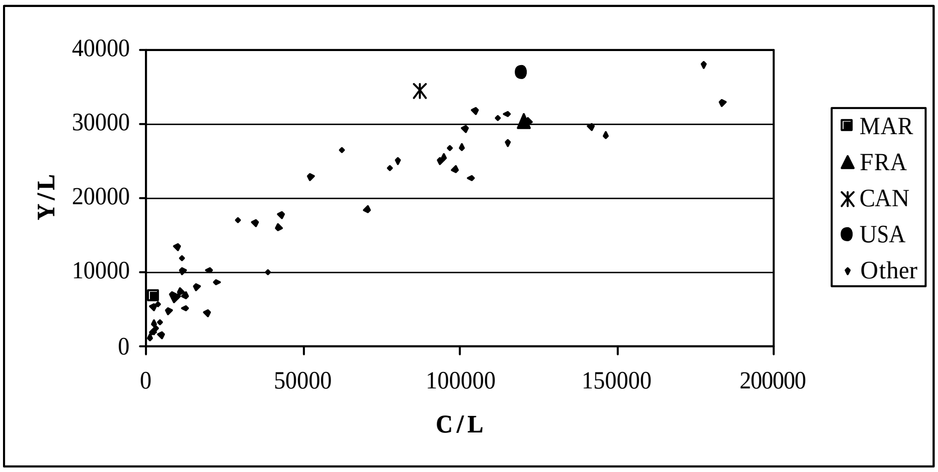
	Actual labor productivity growth		Assimilation		Creating spillover potential		Innovation	
	Miracles	Disasters	Miracles	Disasters	Miracles	Disasters	Miracles	Disasters
1970-1990	Thailand Hong Kong Taiwan South Korea	Zambia Madagascar Peru Jamaica	Hong Kong	Zimbabwe Chile Dominican Rep. Madagascar Paraguay	South Korea	Zambia Bolivia Jamaica Kenya	Australia Switzerland Norway	Argentina Ivory Coast Guatemala Honduras Jamaica Mauritius Panama Peru
1970-1980	Hong Kong South Korea Yugoslavia Paraquay Taiwan	Zambia Madagascar Peru Jamaica Chile	Hong Kong	Zimbabwe Chile Dominican Rep. South Korea Sri Lanka Malawi	South Korea Dominican Rep. Taiwan	India Jamaica Kenya Madagascar Peru Zambia	Canada Malawi	Argentina Ivory Coast Guatemala Honduras Jamaica Mauritius Madagascar Peru Zambia
1980-1990	Thailand Hong Kong Taiwan South Korea	Zambia Peru Argentina Panama Yugoslavia	Hong Kong Sri Lanka Malawi Bolivia South Korea	Yugoslavia Zimbabwe Madagascar Paraguay	India South Korea	Bolivia Honduras Panama Zambia	Switzerland Chile West Germany Morocco	

Appendix:
Countries in samples, ordered by labor productivity levels in 1970.

Rank 1970	Country	Rank 1980	Rank 1990
1	Malawi	1	1
2	Kenia	3	3
3	India	4	7
4	Madagascar	2	2
5	Zimbabwe	6	5
6	Thailand	8	14
7	Zambia	5	4
8	Ivory Coast	7	6
9	Sri Lanka	9	12
10	Philippines	10	9
11	Honduras	11	8
12	Paraguay	17	13
13	South Korea	18	26
14	Turkey	15	20
15	Mauritius	16	23
16	Morocco	14	15
17	Bolivia	13	11
18	Taiwan	24	30
19	Dominican Republic	19	17
20	Guatemala	20	18
21	Jamaica	12	10
22	Colombia	22	22
23	Yugoslavia	27	21
24	Panama	23	19
25	Portugal	25	27
26	Hongkong	28	32
27	Peru	21	16
28	Greece	29	29
29	Japan	30	31
30	Chile	26	24
31	Ireland	32	34
32	Mexico	33	28
33	Argentina	31	25
34	Iceland	39	36
35	Israel	34	33
36	Spain	36	38
37	Finland	38	41
38	Austria	40	39

39	United Kingdom	35	40
40	Italy	44	47
41	Norway	43	43
42	Denmark	37	35
43	Germany	46	44
44	France	45	46
45	Belgium	48	49
46	Sweden	42	42
47	New Zealand	41	37
48	Canada	50	51
49	Australia	47	45
50	The Netherlands	51	48
51	Luxembourg	49	53
52	Switzerland	52	50
53	United States	53	52

Figure 1: Labor Productivity Levels and Capital Intensity Levels in 1990 (53 countries)



Notes: C/L = Producer durable capital stock per worker (in 1985 International $)
Y/L = GDP per worker (in 1985 International $)

Figure 2: Labor productivity growth decomposition

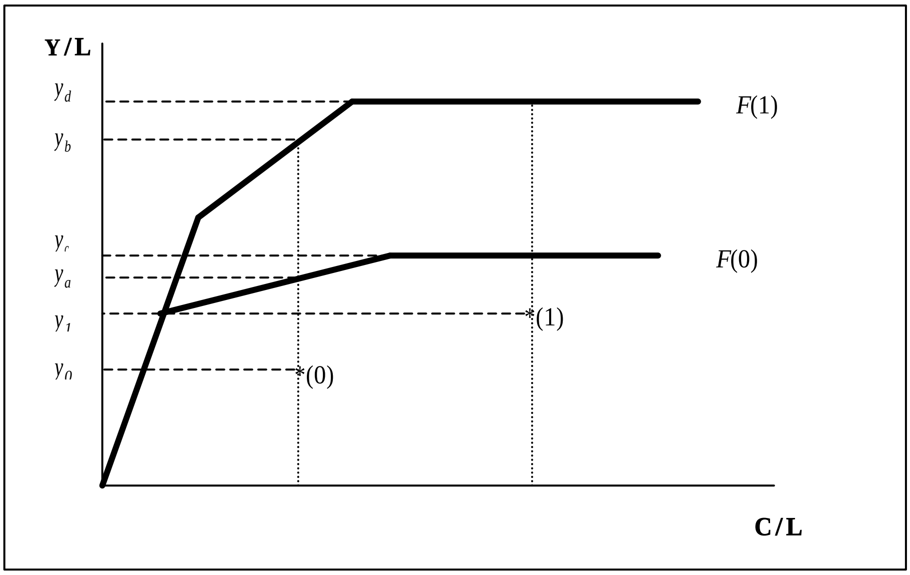


Figure 3: Movement of Frontier Labor Productivity Levels for a Range of Technologies, 1970-1990 (1970 =100)

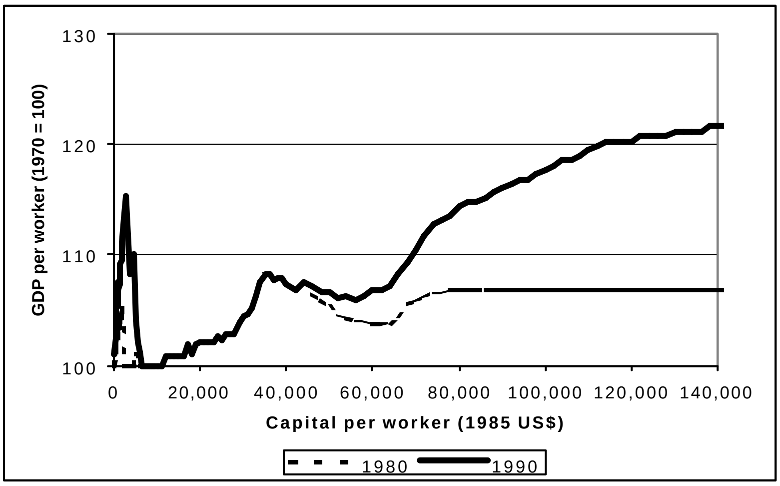
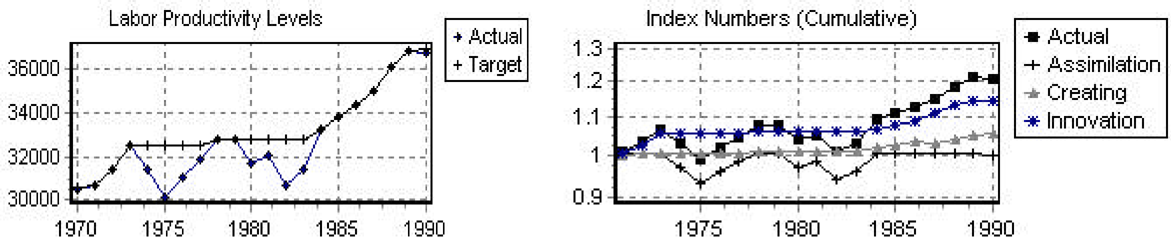
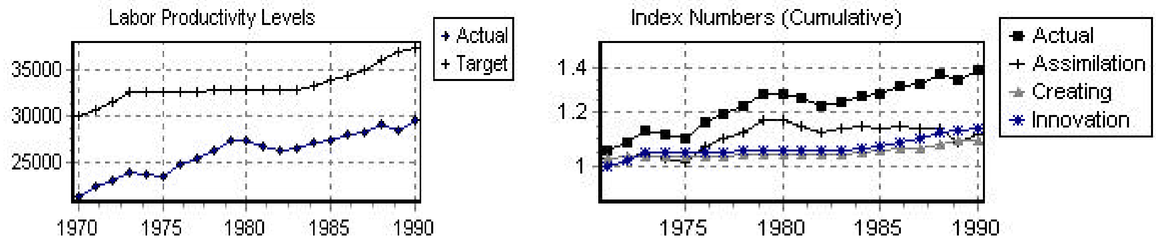


Figure 4 Movement of target and actual labor productivity levels, and decomposition of actual labor productivity growth (1970 = 1), 1970-1990

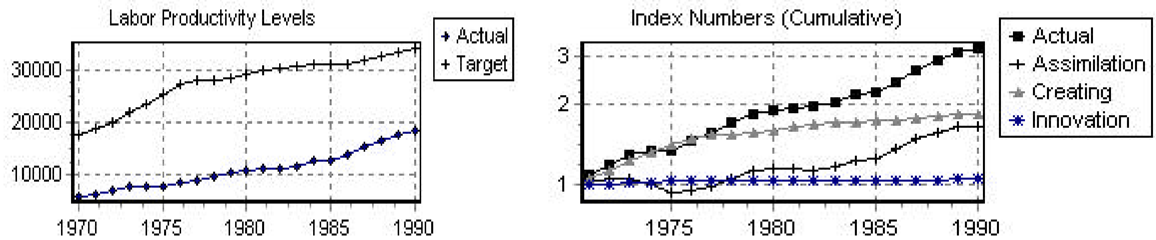
(a) USA



(b) West-Germany



(c) Taiwan



(d) Mexico

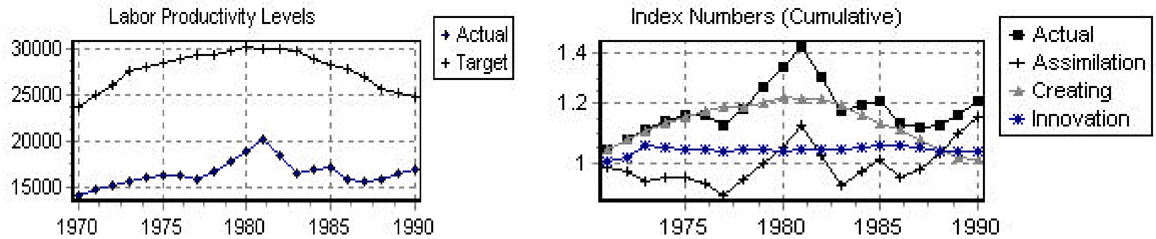


Figure 5a: Means of Ratios.

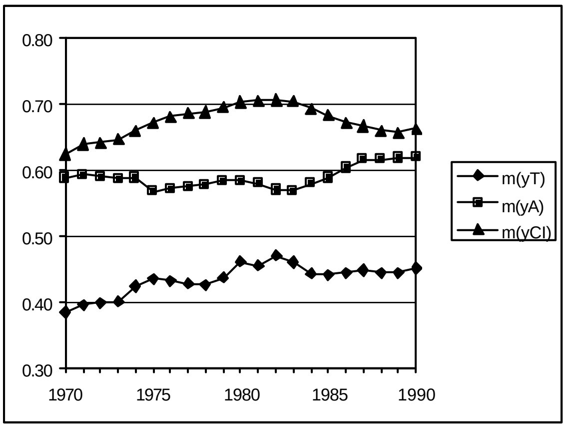


Figure 5b: Standard Deviations of Ratios.

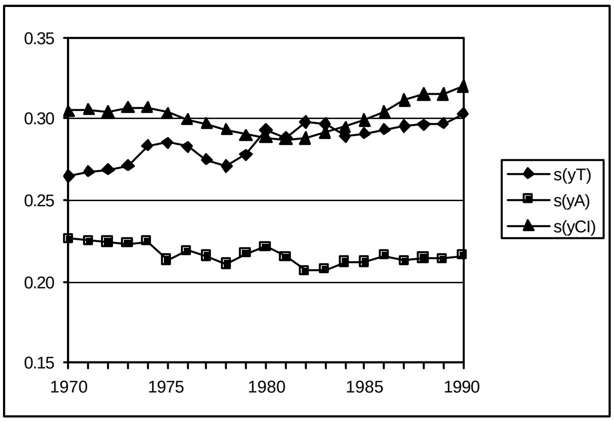
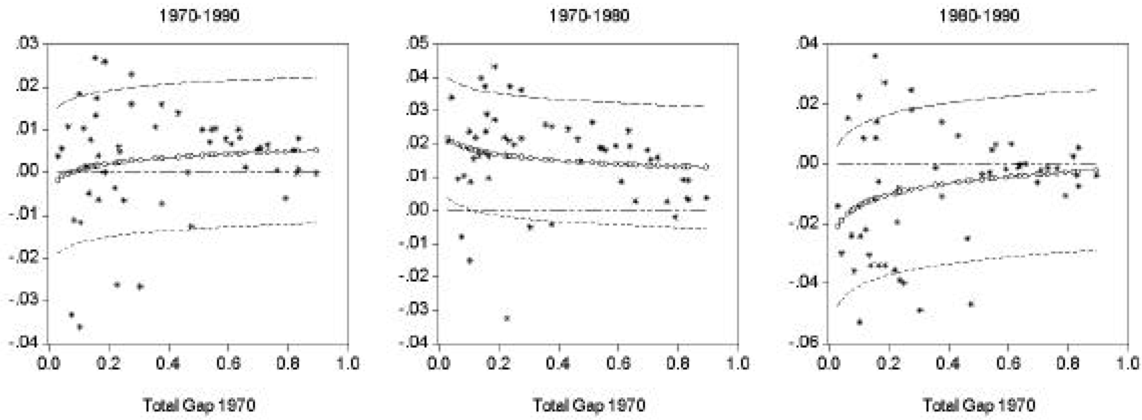


Figure 6a-6c: Labor productivity growth rates relative to US.



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